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Credibility-based rescheduling model in a double-track railway network: a fuzzy reliable optimization approach

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ABSTRACT

Using a space–time network to represent the choice of train trajectories, this paper proposes a fuzzy optimization framework to reschedule trains in a double-track railway network when the capacity reduction is caused by a low-probability incident. We explicitly introduce a fuzzy variable-based recovery time to capture the uncertainty of incident duration based on professional judgements or empirical estimates. The problem is then formulated as a credibilistic two-stage fuzzy 0–1 integer optimization model to find a reliable operational plan for emergency response guidance. The first stage of the model aims to generate a traversing order on the incident link, and meanwhile the second stage adaptively generates optimized schedules to evaluate the operational plan. Crisp equivalents of mathematical models are further investigated to simplify solution methodologies. The numerical experiments, which are solved by using the GAMS optimization software, demonstrate the effectiveness and efficiency of the proposed approaches.

1. Introduction

1.1. Motivation

A variety of factors can lead to capacity reductions in railway transportation networks, such as bad weather, geography disasters, equipment failures, track damage, etc. When an incident occurs, the original pre-trip train timetable might potentially be ineffective, and an efficient rescheduling method is needed for recovering the traffic system. The train rescheduling problem focuses on generating an optimal timetable for the impacted trains in the railway network such that the recovered transportation can be operated optimally and safely. In practice, however, rescheduling process is actually a challenging problem for train dispatchers and engineers due to a large number of complicated constraints.

When an incident takes place, the incident duration is usually recognized as a crucial coefficient to evaluate the severity of the situation. Unlike constant parameters that are precisely given, there may be some vagueness associated with the incident duration, as a result of inherent uncertainties in incomplete a priori information or inaccurate methods of predicting recovery time. To describe uncertainties mathematically, random variables can be used to represent the information inaccuracy based on the statistic methodologies if the sample data size is sufficiently large to estimate the corresponding probability distributions. Otherwise, it is practically suitable to treat the incident duration as a fuzzy variable by professional judgments or empirical estimates, owing to the shortage of sample data (or even no-sample). Focusing on creating a reliable rescheduling strategy, how to effectively reschedule the impacted trains with fuzzy incident duration is a practically important and theoretical challenging issue for the real-world applications. This research will address this problem explicitly.

1.2. Literature review

Over the last decades, the train scheduling/rescheduling problem, which is included in the framework of the job shop scheduling problem and its variants (i.e., see [12,6,28,29,43,32,41]), has attracted tremendous attention from numerous researchers due to its importance in operating and managing railroad systems. Two classes of scheduling methodologies have been developed to generate optimal/close-to-optimal train schedules up to now, namely, (1) deterministic scheduling with constant parameters, and (2) robust (or uncertain) scheduling with disturbance or uncertain variables. For deterministic scheduling, all the involved parameters in mathematical formulations are assumed to be constants. The problem is often formulated as a mixed integer programming model (MIP) or an integer linear programming model (ILP), in which a schedule can be evaluated according to various objective functions, such as (1) total delay time

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[14,15,18], (2) total travel time [5,43], (3) fuel consumption cost [13,37], etc. In particular, the existing scheduling algorithms are typically used to provide either a high-performance schedule or a near-optimal solution, including simulation methods by Dorfman and Medanic [8], Li et al. [18], Xu et al. [33], heuristic algorithms by Lee and Chen [19], Higgins et al. [15], Chung et al. [7], Hong et al. [17], branch and bound algorithms by Higgin et al. [14], Zhou and Zhong [43], and Lagrangian Relaxation by Cacchiani et al. [1].

As a complex system, the railway transportation might often be disturbed by a variety of uncertain factors, leading to the ineffectiveness and infeasibility of train schedules. Because of this, many researchers begin to investigate the robustness of railway timetables in recent years, in which the aim is to generate robust timetables for trains, i.e., to find a schedule that avoids, in case of disruptions in the railway network, delay propagation as much as possible [3]. As for the modeling methods, Kroon et al. [16] first proposed a stochastic optimization model to improve the robustness of a given cyclic railway timetable. This model can allocate the time supplements and the buffer times in a given timetable so as to make it maximally robust against stochastic disturbances. Besides, through combining linear programming (LP) and ad hoc stochastic programming/robust optimization techniques, Fischetti et al. [10,11] proposed and analyzed four different methods to improve the robustness of a given train timetable solution for the aperiodic (noncyclic) case. Cacchiani and Toth [3] gave a survey of the main studies dealing with the train timetabling problem in its nominal and robust versions. They also summarized different approaches for constructing robust timetables, including stochastic optimization, light robustness, recoverable robustness, delay management, bi-criteria and Lagrangian-based approaches, and metaheuristics. Yang et al. [34] investigated the train timetable problem considering fuzzy quantity of passengers, and formulated the problem as an expected multi-objective model. Yang et al. [35] proposed several models with different criteria to handle the randomness in the train scheduling problem. More recently, Meng and Zhou [26] presented a two-stage stochastic model for finding the robust rescheduling strategies when an incident occurs on the railway link, where the expected value criterion was employed to evaluate the rescheduling generation. Cacchiani et al. [2] investigated how to modify an existing Lagrangian heuristic to produce robust solutions for train timetabling problem. Caprara et al. [4] proposed different models to compute robust routing schedules, and a simulation framework was employed to evaluate the effectiveness of models and algorithms through using real-world data provided by the main Italian Railway Infrastructure Manager. Salido et al. [30] presented the robustness problem from the point of view of railway operators and proposed analytical and simulation methods to measure robustness in a single railway line. In addition, Yang et al. [38] treated the duration of the incident as a discrete fuzzy variable, and formulated the rescheduling problem as a two-stage expected fuzzy optimization model on a two-way double-track railway line.

1.3. *Proposed approaches*

To the best of our knowledge, the majority of existing literature devotes to generating the robust train schedules under the consideration of the stochastic disturbance and specific solution methodologies. To effectively handle fuzziness in the traffic system, Yang et al. [38] first introduced a fuzzy expectation-based two-stage optimization model to create a robust rescheduling strategy in the literature. Their research, however, does not consider the dwelling capacity of each station due to inherent difficulties of representing this constraint as a linear form. Moreover, although the expected value criterion is of particular interest because it can be used to reduce a fuzzy problem to a deterministic one, it still may not be appropriate in all situations. Actually, if a rescheduled optimal timetable can be used many times, in the long-run, the average total delay will be shorter than that of using other timetables. As the application of a rescheduled timetable always involves a single or only a few trials, minimizing expected delay is in essential not a favorite criterion to evaluate practical rescheduling strategies. Aiming to decrease the decision risks, in this research we are particularly interested in how to generate the reliable rescheduling with the minimized risk if the incident duration is estimated as a fuzzy variable. This paper intends to make the following contributions to the growing body of the train rescheduling problem in the literature.

(1) As a new approach, the credibility-based reliable optimization is first introduced to set up a rigorous coordinated routing formulation for seeking a reliable rescheduling plan after the incident, where a fuzzy variable is used to characterize the incident duration estimated by professional judgments. In detail, to show space–time characteristics of trains trajectories, the physical railway network is generalized to a variety of space–time networks associated with different trains. The problem is then transformed into a coordinated routing problem and formulated as a fuzzy two-stage 0–1 integer programming model with system constraints, such as flow balance constraints, headway constraints, dwelling time constraints, etc. Compared with the existing researches, the proposed approach especially considers the station capacity in the model through introducing waiting arcs at each station. Since the model is expressed as a 0–1 integer programming, it can be expected to solve with the aid of commercial optimization softwares.

(2) Another emphasis is the property analysis of the models and solution methods. To evaluate fuzzy risks mathematically, two different objectives, namely the minimal α-critical value and maximal credibility, are proposed based on the fuzzy credibility measure. In particular, a proposition is proved to show the equivalent relationship of these two evaluation indices under some given conditions. A simplified equivalent formulation is also deduced based on the property analysis of the mathematical model. The problem is then coded in the GAMS optimization software to search for a close-to-optimal solution. The numerical experiments demonstrate that the proposed approaches can effectively find reliable rescheduling plans within reasonable computational time.

To understand the focuses of this research clearly, the detailed features will be summarized in Table 1 in comparison with some closely related works in the literature.

More specifically, the major difference between this research and Meng and Zhou [26] can be summarized in the following four aspects. (1) *Different uncertainty representation methods*: As for the rescheduling problem by Meng and Zhou [26], they assume that the incident duration is a random variable, and handle the problem by a random programming framework based method. Note that the incident duration is often practically estimated as a fuzzy variable by professional judgments, such as “about two hours”, “no less than 50 min”, etc., which is typically different from the randomness. With this concern, this paper formulates the problem within the framework of fuzzy optimization, which is essentially different from that proposed by Meng and Zhou [26]. (2) *Different transportation environment*: In this paper, the traffic environment is a network instead of single-track railway line which is investigated by Meng and Zhou [26]. (3) *Different constraint conditions*: We further consider some other practically important constraints in rescheduling process, for instance close-to-favorite-schedule constraints, dwelling capacity constraints, etc. (4) *Different evaluation criteria*: The objective function in Meng and Zhou [26] is the expected total delay in the rescheduling process,